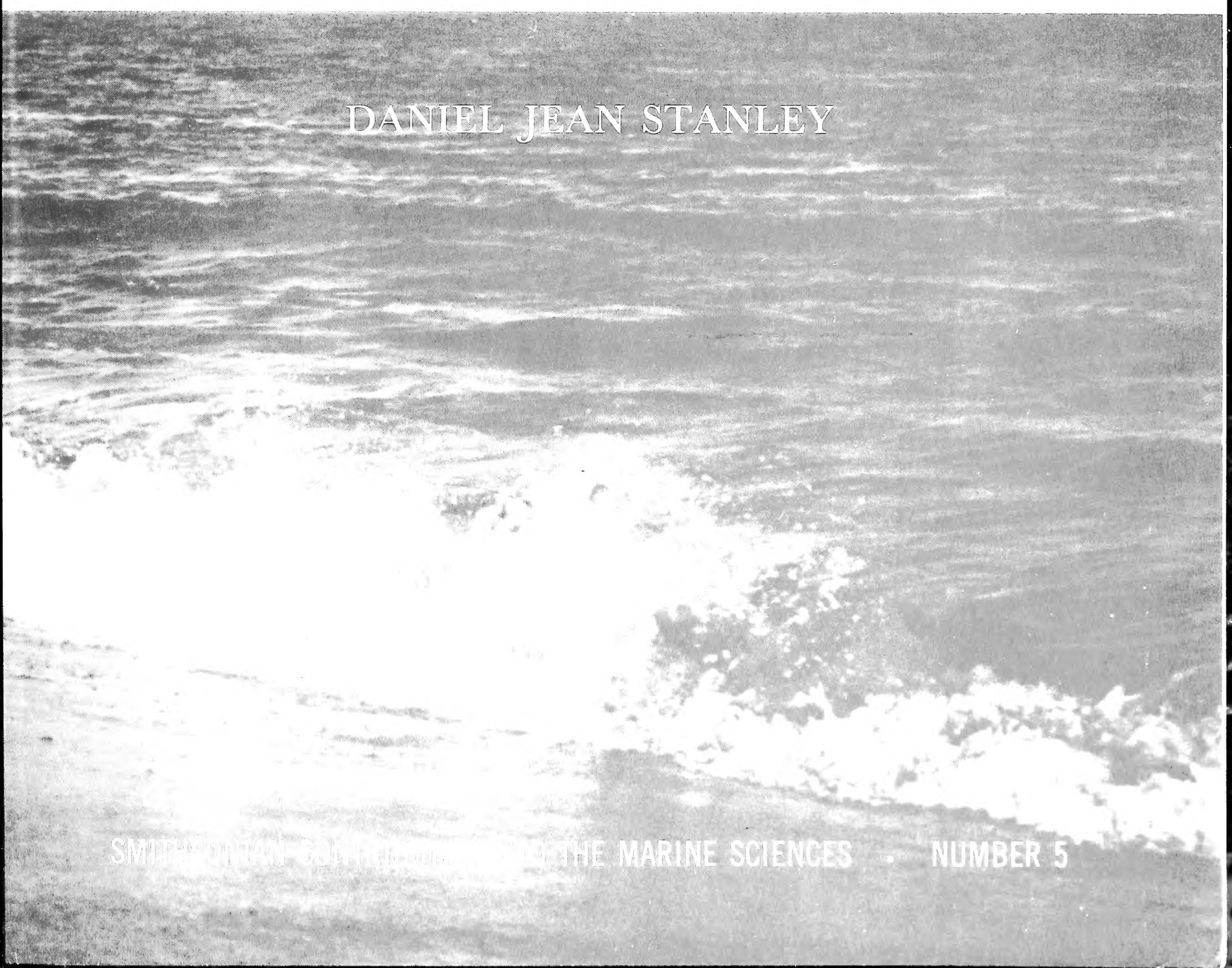
The Saint-Antonin Conglomerate in the Maritime Alps: A Model for Coarse Sedimentation on a Submarine Slope



DANIEL JEAN STANLEY

SMITHSONIAN CONTRIBUTIONS TO THE MARINE SCIENCES · NUMBER 5

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The Saint-Antonin Conglomerate in the Maritime Alps: A Model for Coarse Sedimentation on a Submarine Slope

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ABSTRACT

Stanley, Daniel Jean. The Saint-Antonin Conglomerate in the Maritime Alps: A Model for Coarse Sedimentation on a Submarine Slope. *Smithsonian Contributions to the Marine Sciences*, number 5, 25 pages, 12 figures, 1 table, 1980.—The Upper Eocene to Lower Oligocene Saint-Antonin Conglomerate, a formation more than 1000 m thick well exposed in the French Maritime Alps, about 30 km north of the Mediterranean coast, comprises coarsening-upward successions, or megasequences, of silty shale-siltstone, sandstone and conglomerate sections. The megasequences include coarse channelized deposits associated with coarse lenticular and fine-grained sheet facies that are identified as migrating channels and lobe and channel overflow deposits. Microfossils in the finer-grained units indicate dispersal in an open marine, outer shelf to upper bathyal environment where minimal depths ranged from 100 to 200 m. The spatial and temporal distribution patterns of facies successions, assemblage of stratification types and sedimentary structures, and petrology of the various textural grades indicate submarine progradation on a slope, or in a slope basin, seaward of a fan delta system. The Saint-Antonin Conglomerate is more similar to alluvial fans than to some of the gravel-rich submarine fan deposits that accumulate on a gentle gradient at the base of a slope. The coarsening-upward megasequences record a strong tectonic overprint, including a northward shift of the basin margin on which these strata were deposited, concurrent andesitic flows and structurally-induced fan delta switching on the adjacent land. This latter phenomenon was largely responsible for the irregular back-and-forth migration of the sandstone and gravel-rich tongues on the upper slope. Emplacement of poorly sorted (disorganized) conglomerates and pebbly sandstones, and of strata displaying crudely stratified inverse grading or preferred clast fabric, was largely by debris flow and associated high-concentration dispersions. Slumping, turbulent flows with some bed-load traction and turbidity currents also were effective mechanisms for the transport of sediment to proximal depositional sites on the slope. Modern counterparts of the Saint-Antonin Conglomerate are probably to be found on the leading edge of plates, rift margins and other tectonically-active coastal chain-bounded margins where coarse terrigenous sediments bypass narrow shelves and are transported directly on steep mobile slopes.

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Introduction

The origin of deep marine gravel facies remains poorly understood. On modern subaqueous slopes, pebble- and cobble-rich deposits constitute channelized tongues in canyons and fan valleys (Shepard and Dill, 1966; Whitaker, 1976; Stanley and Kelling, 1978), talus on seamount flanks, oceanic ridges, and arc settings (Heezen and Hollister, 1971), progradational wedges off reefs and carbonate shelves (Cook and Enos, 1977), and ice-rafted patches at high latitudes (Brundage, et al., 1967). Most studies of gravity-emplaced, coarse terrigenous sediments on modern slopes emphasize channelized settings where they are frequently observed and dredged (Gennesseaux, 1966; Hersey, 1967; Stanley, 1974; Heezen and Hollister, 1971), and recorded on high-resolution subbottom profiles (Embley, 1976). Gravels, pebbly sands and pebbly muds also are recovered at and beyond the base of slopes, most commonly in the vicinity of submarine valleys (Shepard and Dill, 1966). Coarse surficial deposits are difficult to core, and in consequence, little is known of their structure and fabric or of the transport mechanisms responsible for their emplacement.

Attributes of pebble-rich slope sequences are more readily investigated in the rock record, and here most attention has been paid to deep marine channelized canyon and fan valley conglomerates and to coarse base-of slope, rise and fan lobe sequences. Information on gravel-rich sequences in more proximal and non-channeled submarine slope environments is actually quite limited. The present study identifies such a deposit, the Saint-Antonin Conglomerate (anglicized from "conglomérats de Saint-Antonin" and "formations détritiques de Saint-Antonin"; cf. de Laparrent, 1938; Stanley, 1961; Bodelle, 1971), a coarse Neogene terrigenous formation in southeastern France (Figure 1). This formation, the youngest marine complex in this sector of the Maritime Alps, crops out in an elongate syncline about 15 km wide near the villages of Saint Antonin, Collongues, and La Rochette (Figure 1). The large size of metamorphic and igneous debris provides some indication of proximality to source and transport by powerful torrential flow (Vernet, 1964a). Most workers who previously examined this formation have asserted that its conglomeratic and pebbly sandstone series were emplaced close to a site of sediment entry on the margin of

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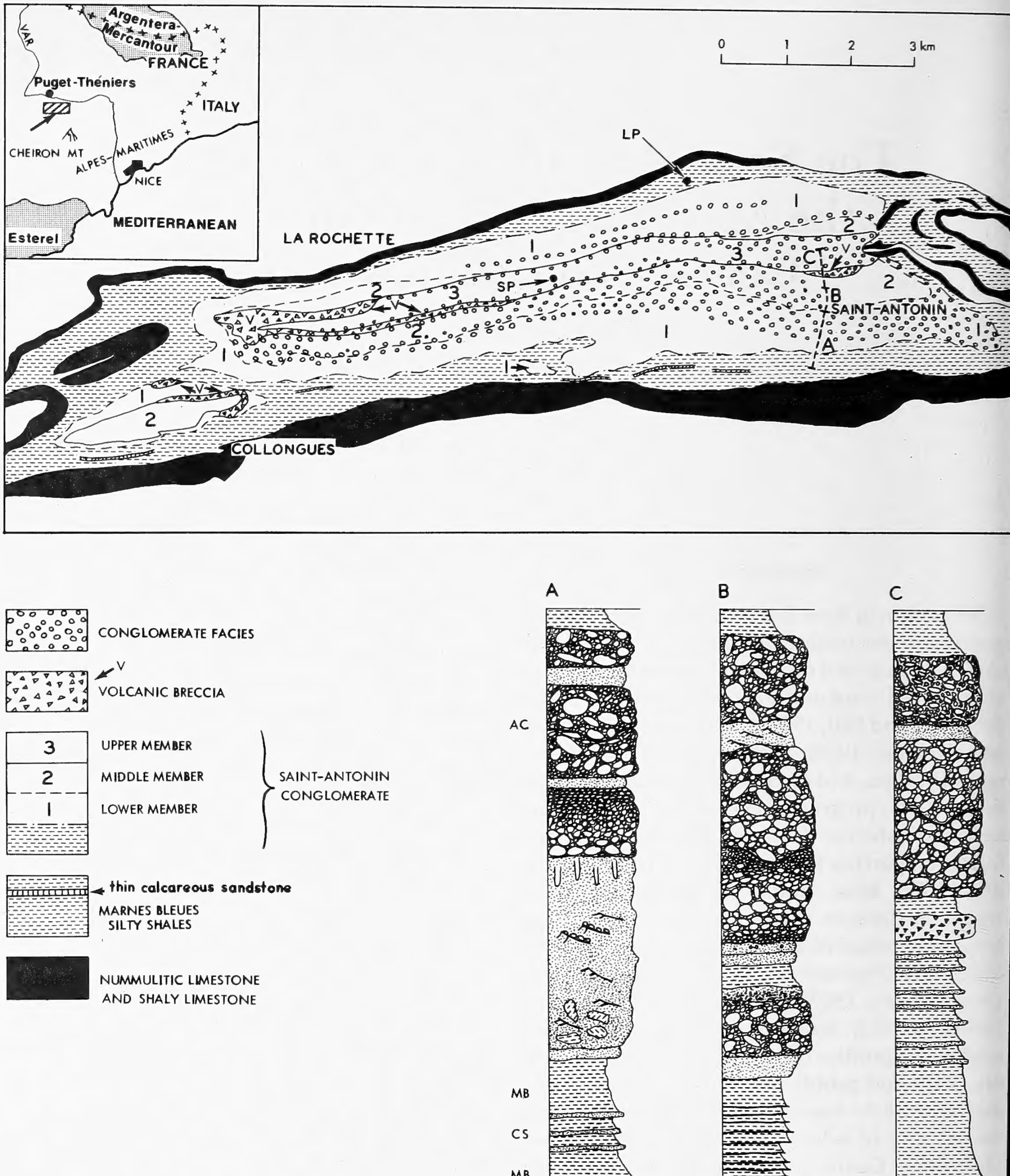

FIGURE 1.—Geological map of Saint-Antonin syncline study area in French Maritime Alps showing three stratigraphic members (1, 2, 3) of the Saint-Antonin Conglomerate and location of major conglomerate sequences (simplified from Bodelle, 1971). (LP = La Penne; SP = Saint-Pierre; A, B, C = simplified columnar depictions of three major upward-coarsening megasequences mapped along SSW-NNE transect in vicinity of village Saint-Antonin; MB = Marnes bleues silty shales; CS = Calcareous sandstone; AC = first appearance of andesitic cobbles in megasequence A.)

a tectonically active basin.

The coarse strata have been interpreted in several ways: as alluvial and lacustrine deposits (de Lapparent, 1938), fluvio-deltaic series (J.-P. Bertrand, pers. comm., 1974, 1976), marine nearshore deposits (Boussac, 1912; Bodelle, 1971), and marine delta-front platform and proximal margin deposits (Stanley, 1975). The present study focuses on the temporal arrangement of the terrigenous units as thick coarsening-upward successions, or megasequences, and on the spatial distribution comparable to some alluvial and submarine fan facies. On the basis of such lithofacies successions and their assemblages of stratification types and sedimentary structures, I propose a marine slope depositional origin for the Saint-Antonin Conglomerate. The depositional model involves (a) shelf bypassing and direct accumulation of gravelly fan delta sediment on the margin of a structurally mobile basin at depths greater than formerly envisioned, possibly in a depression or perched slope basin, and (b) fan-like emplacement of coarse sediment by slumping, debris flows and associated high-concentration dispersions, and by traction processes.

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Geological Setting

The Saint-Antonin syncline is located approximately 9 km north of the Cheiron Mountain Chain, and about 4 km south of the Var River and 30 km northwest of the city of Nice on the Mediterranean coast (Figure 1). This structure lies within a sector of the Arc de Castellane tectonic belt where trends are oriented primarily east-west (Goguel, 1936). Most workers have assigned an Upper Eocene (Priabonian) age to the Marnes bleues marl and shale section underlying the more than 1000 m of poorly cemented sandstone and conglomerate (de Lapparent, 1938). The age of the coarse series is not as well defined. On the basis of fauna and petrology Vernet (1964b) attributes an Oligocene age to the massive bedded sandstones and pebbly mudstones above the Marnes bleues, and a lower Miocene age to the overlying coarser conglomeratic series and associated extrusive volcanics. In a more recent biostratigraphic analysis, Bodelle (1971) assigns a latest Eocene–earliest Oligocene (*Globigerina gortanii* zone) age to the sandstone, pebbly sandstone, and lower conglomeratic series without volcanics (his "première formation détritique"), and a lower Oligocene age to the thick conglomerate sequences with volcanics (his "seconde" and "troisième formation détritique").

Field measurements of sedimentary structures indicate a predominant SE to NW paleocurrent trend (Kuenen, et al., 1957; Stanley, 1961; Bodelle, 1971). A southern provenance is corroborated by the composition of heavy and light sand-size material and of cobbles and boulders (de Lapparent, 1938; Stanley, 1961, 1964; Vernet, 1964b; Bodelle, 1971). Sources include both igneous and metamorphic terrains in the Maures-Esterel Massif located about 30 to 50 km to the south of the Saint Antonin exposures, and sedimentary (largely Mesozoic limestone and shale) formations in the adjacent Maritime Alps. However, the origin of ophiolitic and other Saint-Antonin cobble and boulder lithologies, particularly granitic rock types that do not occur in the Argentera-Mercantour and Maures-Esterel massifs (shown on the inset map in Figure 1), is problematical: a derivation from once-exposed crystalline terrains to the southeast and east, areas presently covered by the Ligurian Sea or buried

by the Helminthoid Flysch, or both, has been suggested by the above-cited authors.

On the basis of geodynamic and paleogeographic considerations it would appear that Corsica and its northern and western extensions were once much closer to the present French Provençal coast (Kuenen, 1959; Stanley, 1961; Nairn and Westphal, 1968; Bodelle, 1971; Alvarez, 1972; Moullade, 1978). The pre-Miocene reconstructions that place the Corsica-Sardinia land mass close to, or against, southern Europe would delineate a much enlarged source area that could have furnished the large volumes of coarse sediment transported northward to the Maritime Alps and northern Apennines at the end of the Eocene and in the early Oligocene (Stanley and Mutti, 1968; Stanley, et al., 1978, fig. 17). The best fit between Corsica and the Provençal margin brings Hercynian and Alpine series of Corsica to within 60 to 70 km south and southeast of the Saint Antonin syncline (Bodelle, 1971, fig. 210). This scheme, still a speculative one, might well account for the large size of Corsican-type crystalline debris and the recorded dispersal pattern toward the NW.

As presently envisioned, deposition of the lower sandstone, pebbly sandstone, and the first coarse conglomeratic sequences of the Saint-Antonin Conglomerate was contemporaneous and genetically related to the thick sandstone series ("grès d'Annot") to the north and northwest in the marine Annot Basin (de Lapparent, 1938; Stanley, 1961, 1975). The mid- and upper terrigenous series of the Saint-Antonin Conglomerate record the final stages of marine deposition in this part of the Maritime Alps; as these sequences accumulated in the Saint-Antonin region, the Nummulitic Sea had largely receded from the Annot Basin (Bodelle, 1971, figs. 206–208). Large volumes of andesitic debris introduced from local volcanic centers, and unconformities within the conglomeratic series, amply document local emergence and structural displacement of this region during the early part of the Oligocene. Following deposition vigorous Middle and Upper Oligocene folding and thrusting prevailed, and further intense structural deformation affected the region in the Miocene and Pliocene during regional uplift of the southern Alps and evolution of the Ligurian Sea.

General Stratigraphic Framework

The coarse conglomerate series in the Saint-Antonin syncline were deposited above a lower Tertiary sequence consisting, from base up, of Eocene Nummulitic limestone ("calcaires à Nummulites") and shale-limestone series ("calcaires argilo-sableux"), thick (about 200 to 300 m) Upper Eocene gray to bluish silty shales ("Marnes bleues"), and massive bedded sandstones (Log A in Figure 1). These series tend to be best exposed on the southern, more gently dipping (30° to 40°) limb of the syncline. The stratigraphy, petrography, and faunal content of these formations in the Saint Antonin syncline and adjacent areas have been detailed by Bodelle (1971) and Campredon (1972).

The Marnes bleues marls and shales include a variable number of thin (most 5–25 cm; a few to 100 cm), calcareous siltstones and sandstones and calcarenites about half-way upsection in the southern part of the syncline, southwest of Saint-Antonin and northeast of Collongues (units CS in log A, Figure 1). These coarser units, alternating with gray-blue silty shales, commonly contain plant matter, mica, glauconite, mollusc fragments, and foraminifera, including both large and small benthonic and planktonic tests. Analysis of this facies and associated microfossil assemblages suggests deposition at neritic depths, possibly 100 m or less (Bodelle, 1971). The calcareous sandstone and detrital limestone units accumulated in an environment affected by bottom currents and favorable to benthic organisms as recorded by the bioturbated base, moderate to highly cross-stratified internal structure, and rippled upper bedding surface. A few of the calcareous sandstone beds are not cross-stratified but moderately graded with sole markings indicating transport primarily toward the NW; these units, resembling poorly developed turbidites, record a more rapid introduction and burial of sand on the margin.

The massive sandstone and overlying conglomerate facies in the eastern part of the syncline are well exposed along the small road (D-427) leading to Saint-Antonin. On the basis of this and other cross-syncline transects, Bodelle (1971; 158–171) has identified three members briefly described below (their distribution is depicted on the map in Figure 1). The name Saint-Antonin Conglomerate is applied here as the formation name for the stratigraphic section formed by the three members.

LOWER MEMBER (about 400 m thick).—The lower 120 m of this member comprises light-colored, friable (argillaceous and calcareous cement), coarse-grained, poorly sorted sandstone and pebbly sandstone. Common features include cross-stratification (foreset laminations oriented toward the W and NW) with thin shaly interbeds (Figure 2A). Asymmetric ripple surfaces (current toward the W and NW) and plant-rich layers are common (Figure 2B). The massive sandstone strata are amalgamated units that consist of individual layers 30 to over 100 cm thick. Erosional features (cut-and-fill, small to moderate-size channels, large rip-up clasts) that abound within most units record migrating channel processes. These sandstones display both horizontal and forset stratification, and the small pebbles commonly concentrated along these surfaces provide evidence of emplacement by traction mechanisms or represent lag deposits. A few thin (< 1 m) individual sandstone layers, poorly to moderately graded with sole markings, including flame structures, also are observed. The first major conglomerate is a 5 m-thick, sharp-based, poorly sorted, matrix-supported cobble and boulder mudstone showing poorly developed vertical grading of the larger debris (Figure 2C). Coarse debris of diverse provenance include subrounded to well-rounded granite, rhyolite, and other igneous and metamorphic lithologies, and minor amounts of sedimentary clasts. This unit is followed by a thick succession of sandstone, pebbly sandstone, and conglomeratic strata of variable thickness, coarseness, and configuration (Figure 2D); some are sharp-based lenticular units and others channelized. Further description of the lithofacies in this and the other two members are presented in following sections.

MIDDLE MEMBER (about 350 m thick).—The base of this member, a coarse debris, matrix-supported conglomerate, is identified by andesitic cobbles and boulders (Figure 3B) of local derivation (Sant-Antonin extrusive volcanics have been described by Vernet, 1964a and Bodelle, 1971) that complement polymictic crystalline and sedimentary debris comparable to that of the Lower Member. Sandstone strata and the sandstone matrix in conglomerates tend to be darker (ochre) than those in the lower member, in part reflecting a compositional change: higher proportions of iron-stained grains, amphiboles, pyroxenes, and plagioclases. A thick (about 50 m) series of alternating laminated siltstones and shales is interbedded between conglomerate beds; the finer-grained layers include a benthic and planktonic foraminiferal fauna (Table 1) confirming the marine origin of this unit. Shales, in turn, are covered by a thick section of massive amalgamated and graded sandstone types and coarse polymictic conglomerate lenses and channels. A nearly 100-m-thick unit (Figure 2D) comprising large blocks (>1 m in diameter) crops out northeast of the village of Saint Antonin. This coarse composite lens, consisting of laterally discontinuous strata, is in turn covered by about 150 m of silty micaceous shales and laminated siltstones (similar to the upper Marnes bleues shales) and fine-grained sandstones. The base of thin sandstone layers display sole markings, including organic structures and some tool marks, oriented toward the NW. The shales include a mix of fresh and rather poorly preserved planktonic and benthonic foraminifera; the planktonic/benthonic ratio ranges from 0.5 to over 1.0. The shale-siltstone section is partially covered and slightly truncated by an andesitic flow breccia of the type illustrated in Figure 3C. The breccia delineates the top of the Middle Member; where these volcanic flows are absent, the shales are in erosional contact with conglomerates of the Upper Member.

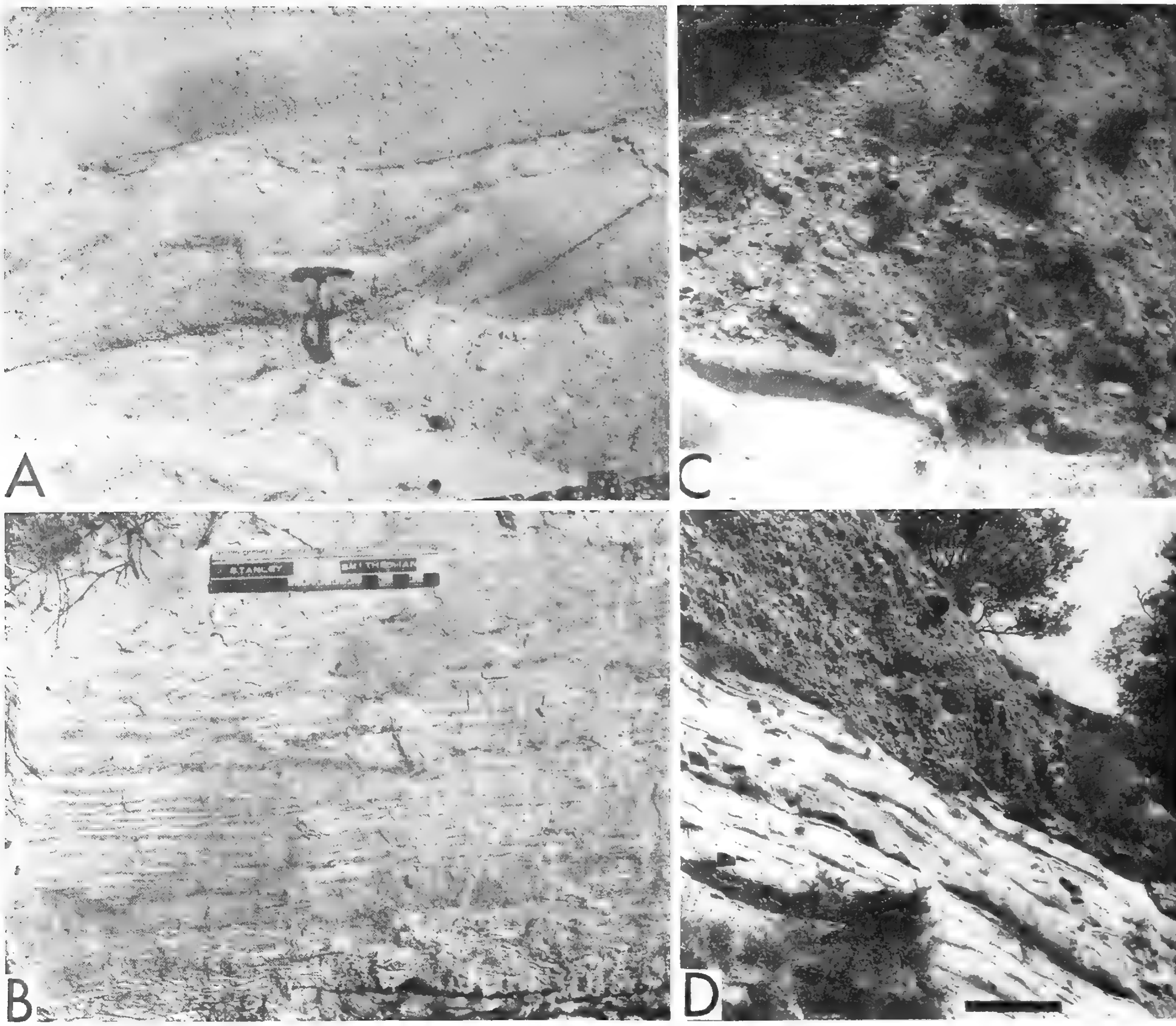

FIGURE 2.—*A, B,* Foreset stratification and sets of ripple lamination oriented toward W and NW, in massive, poorly cemented sandstone section (megasequence A) above Marnes bleues shales along road D-427, SW of village of Saint-Antonin; *C,* first conglomerate bed (sharp based, matrix supported, crudely graded) above massive sandstone section in megasequence A, *D,* interbedded sandstone and clast supported conglomerate strata forming coarse, upper term of megasequence B, NE of Saint-Antonin. (Hammer = 28 cm; ruler scale = 15 cm; bar scale in lower *D* = 100 cm.)

UPPER MEMBER (> 200 m).—This upper term comprises moderately to very coarse conglomerates, both lenticular and channelized. The clasts include most metamorphic and igneous rock types found in the Lower and Middle members, but, in addition, higher proportions of andesitic debris (Figure 3A); the mauve hue to this member is in part due to the abundance of this volcanic component (usually weathered) and Mesozoic and Neogene limestone lithologies. Microfossil faunas in interbedded silty shales indicate an Oligocene age according to Bodelle (1971); these are mixed with tests reworded from mesozoic and older Nummulitic series. Thin gypsum stringers,

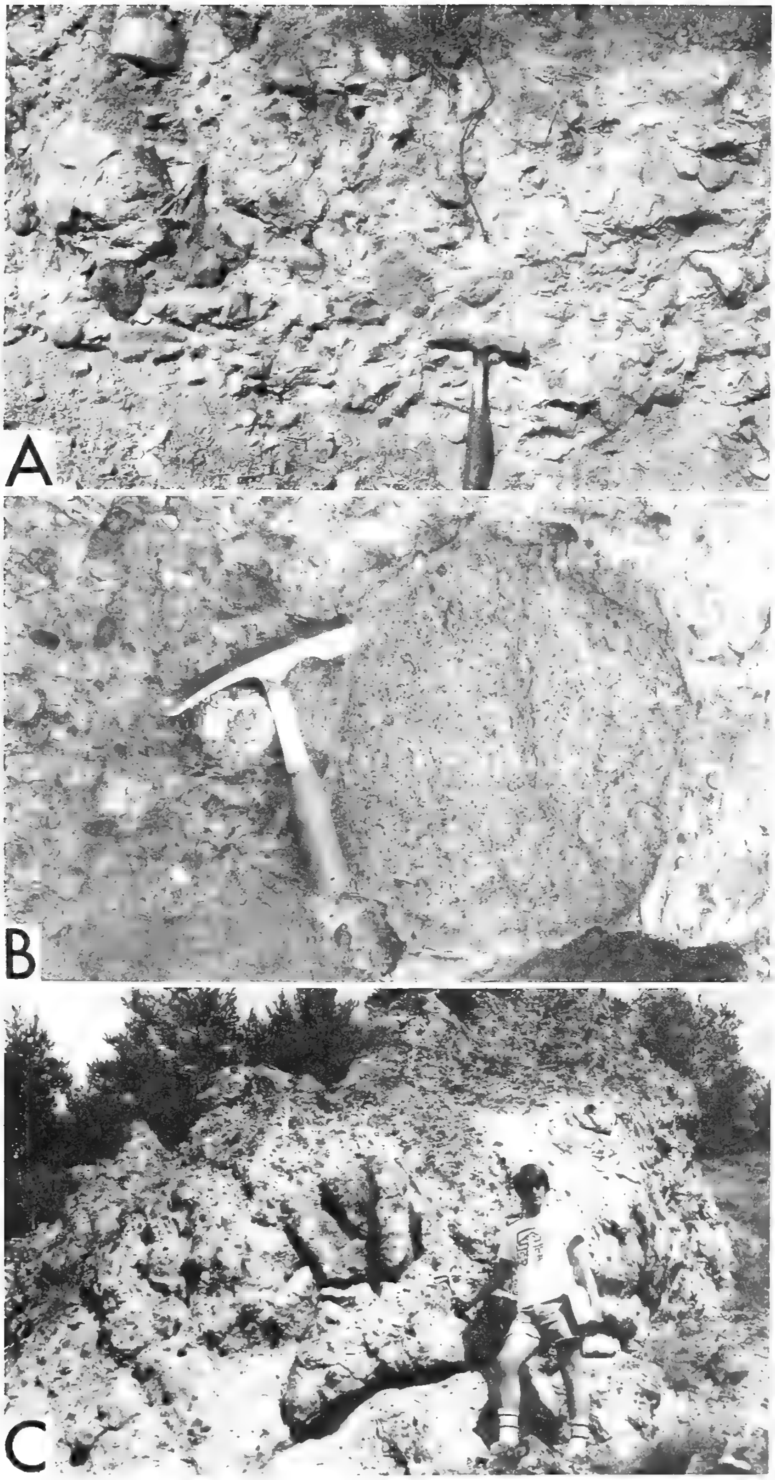

FIGURE 3.—Evidence of syndepositional volcanic activity in Saint-Antonin syncline: *A*, Andesitic cobbles and boulders, in megasequence C, NE of Saint-Antonin; *B*, same, in megasequence A, SW of Saint-Antonin; *C*, andesitic breccia NNW of Collongues, along small road near Fontane.

TABLE 1.—Foraminiferal assemblages in samples collected in megasequences A, B, and C of Saint-Antonin Conglomerate in vicinity of Saint-Antonin (G. Glaçon, pers. comm., 1978)

1. Sample MED-78-2: shale sample in a 5-to-7-m-thick fine-grained section, between 2 conglomerate layer in the upper part of megasequence A, along road D-427, SW of Saint-Antonin.

   Planulina wüllerstorfi (Schwager)
   Uvigerina species
   Cibicides pseudoungerianus (Cushman)
   Cibicides aff. *lobatulus* (Walker and Jacob)
   Robulus serpens (Seguenza)
   Robulus species
   Gyroidina species
   Siphonodosaria verneuili (d'Orbigny)
   Spiroplectammina carinata (d'Orbigny)
   Globigerina sp.

2. Sample MED-78-3: shale sample in a thick siltstone-shale section, base of the lower term of megasequence B, along road D-427, W of Saint-Antonin.

   Robulus serpens (Seguenza)
   Robulus species
   Eponides aff. *umbonatus stellatus* (Silvestri)
   Catapsydrax species

3. Sample MED-78-7: shale sample in a thick siltstone-shale section below the sandstone-conglomerate lenticular units, megasequence B, at the Saint-Antonin village cemetery.

   Eponides aff. *umbonatus stellatus* (Silvestri)
   Globigerina species
   Catapsydrax species

4. Sample MED-78-5: shale sample in a 'flysch-like' siltstone-shale section, lower term of megasequence C, along road D-427, about 1 km NE of Saint-Antonin.

   Trochamminidae
   Globigerina species

5. Sample MED-78-4: shale sample in a 'flysch-like' siltstone-shale section, lower term of megasequence C, along road D-427, about 1.7 km NE of Saint-Antonin.

   Bulimina jarvisi Cushman and Parker
   Gyroidina girardana perampla Cushman and Stainforth
   Osangularia mexicana (Cole)
   Bolivina species
   Nodosaria species
   Vulvulina species
   Catapsydrax unicavus Bolli, Loeblich and Tappan
   Globigerina gortanii praeturritilina Blow and Banner
   Globigerina angiporoides Hornibrook

locally exposed in the uppermost shale section between Miolans and La Penne, record the end of the marine regime in this region.

Facies Organization and Associations

The lithostratigraphic boundaries outlined above serve as datum planes to delineate gross regional facies variations, including strata thickness and debris coarseness, along the E-W depositional strike, north-south transects, and opposite syncline limbs. In the Lower Member, for example, lowermost Oligocene conglomerate lenses are thicker and somewhat coarser in the SE sector (near Saint-Antonin) than to the west and north. Important spatial and temporal changes are not surprising in view of unconformities and stratal pinch-out commonly observed in exposures of the three members. With the exception of some andesitic flow breccias, most individual layers cannot be traced laterally for more than several hundreds of meters, and it is difficult to correlate groups of strata for distances in excess of about 1 km.

A sedimentological interpretation of the Saint-Antonin terrigenous series can be achieved in two steps. The first involves organizing the stratigraphic sections comprised between the upper Marnes bleues shales and top of the Upper Member as defined by Bodelle (1971) into major natural lithofacies successions, or megasequences. Three coarsening-upward megasequences are recognized in the eastern part of the syncline where the stratigraphic sections tend to be more complete and better exposed: (A) silty shale-siltstone alternations→ massive sandstone and pebbly sandstone→ coarser, predominantly conglomeratic series; (B) shale-siltstone alternations→ interbedded sandstone and coarse conglomeratic lenses; and (C) shale-siltstone alternations→ coarse conglomeratic lenses. Generalized columns of megasequence A, B, and C as identified in this study are shown by the logs in Figure 1.

The second step requires identification of the basic components that form these megasequences. Each megasequence includes coarsening-thickening upward and fining-thinning upward sets

formed by three major sedimentary associations: coarse channelized, coarse lenticular, and finer-grained sheet facies.

Coarse Channelized Association.—This association, accounting for 15 to 25 percent of the coarse facies column, includes channel fills 1 to 6 m thick and 10 to over 100 m wide consisting of poorly to moderately sorted, massive clast-supported (Figure 4A,B) and, to a lesser extent, matrix-supported conglomerates (Figure 5A). The fills are for the most part unstratified (disorganized), whereas the upper parts, in some cases, display vague to moderate stratification of the clasts. Clasts include subangular to well-rounded pebbles, cobbles, and boulders over 50 cm in diameter; matrix is sandstone or sandy silty shale. Channelized units truncate by as much as 2 to 3 meters the underlying pebbly sandstones and conglomerates. The axial trend can vary from E-W to S-N, but is most often oriented SE-NW, or approximately parallel with paleocurrent directions measured from stratification structures and/or sole markings in the associated strata. The sizes of the maximum and larger clasts sometimes decrease upward; reverse grading is also noted in some sections. Coarser lag deposits fill the base and lower parts of channels (Figure 4D); shale and sandstone rip-up clasts are common as well. Channel fill units are generally interstratified, and occasionally merge with, regionally more extensive lenticular layers of conglomerate and pebbly sandstone.

Coarse Lenticular Association.—This, the most abundant facies, may account for as much as two-thirds of the coarse-grained column and comprises interbedded conglomerate, pebbly sandstone, and massive sandstone strata (Figures 4C, 5C) that ranged from 1 to 10 m thick. Truncation of underlying units is not as extensive as in the channelized association. Individual strata that form this association can sometimes be traced laterally for at least several hundred meters, unlike channelized units that pinch-out abruptly. As a group, these layers form lens-shaped sequences that exceed 50 m and sometimes 100 m in thickness, and comprise very coarse debris; the latter often consist of granite and rhyolite, usually subrounded to well-rounded. Clasts are commonly 0.3m^3, but blocks as large as 3 m^3 are observed (Figure 4C). More continuous, moderate to well stratified finer-grained sandstone and shale layers (Figure 2D) occur in this association. A broad diversity of coarse lenticular stratal types is encountered: disorganized conglomerates and pebbly sandstone, and organized conglomerates and pebbly sandstones.

Coarse disorganized conglomerates, commonly 1 to 5 m thick, are blanket-shaped strata or lenticular pods that do not show well-defined internal structures, are usually very poorly sorted and matrix supported (large subspherical, subrounded clasts float in a sandstone or muddy sandstone mass). The base of a bed may be flat or slightly truncate underlying layers (Figure 6B); basal cobbles and boulders penetrate the underlying sandstone (Figure 6A). Most elongate clasts generally show no preferred organization.

Coarse organized conglomerates, in contrast with above, display vague to moderately well-defined stratification features and prefered fabric. Larger clasts show inverse graded bedding, or crude inverse-to-normal graded bedding (Figure 5A). The long axis, *a*, of flat elongate pebbles may be parallel or subparallel to flow (Figure 7B) and imbricated (dipping upslope, Figure 6A); in other instances, as on the soles of some conglomerates, the long axis is normal to flow (Figure 7C). Disorganized matrix-supported units may pass upward abruptly or gradually to organized conglomerates; the former situation (Figure 7A) is more commonly observed.

Disorganized pebbly sandstone constitutes a significant proportion of the lenticular association, and these are recognized by the random dispersion of pebbles, typically smaller than 5 cm, in massive bedded, coarse-grained sandstones or muddy sandstones. In most cases clasts are irregularly dispersed (Figure 8C), but in some instances show preferential orientation (Figure 8B) with imbrication (upslope dip) of either the elongate *a* axis or intermediate *b* axis.

Organized pebbly sandstone types comprise

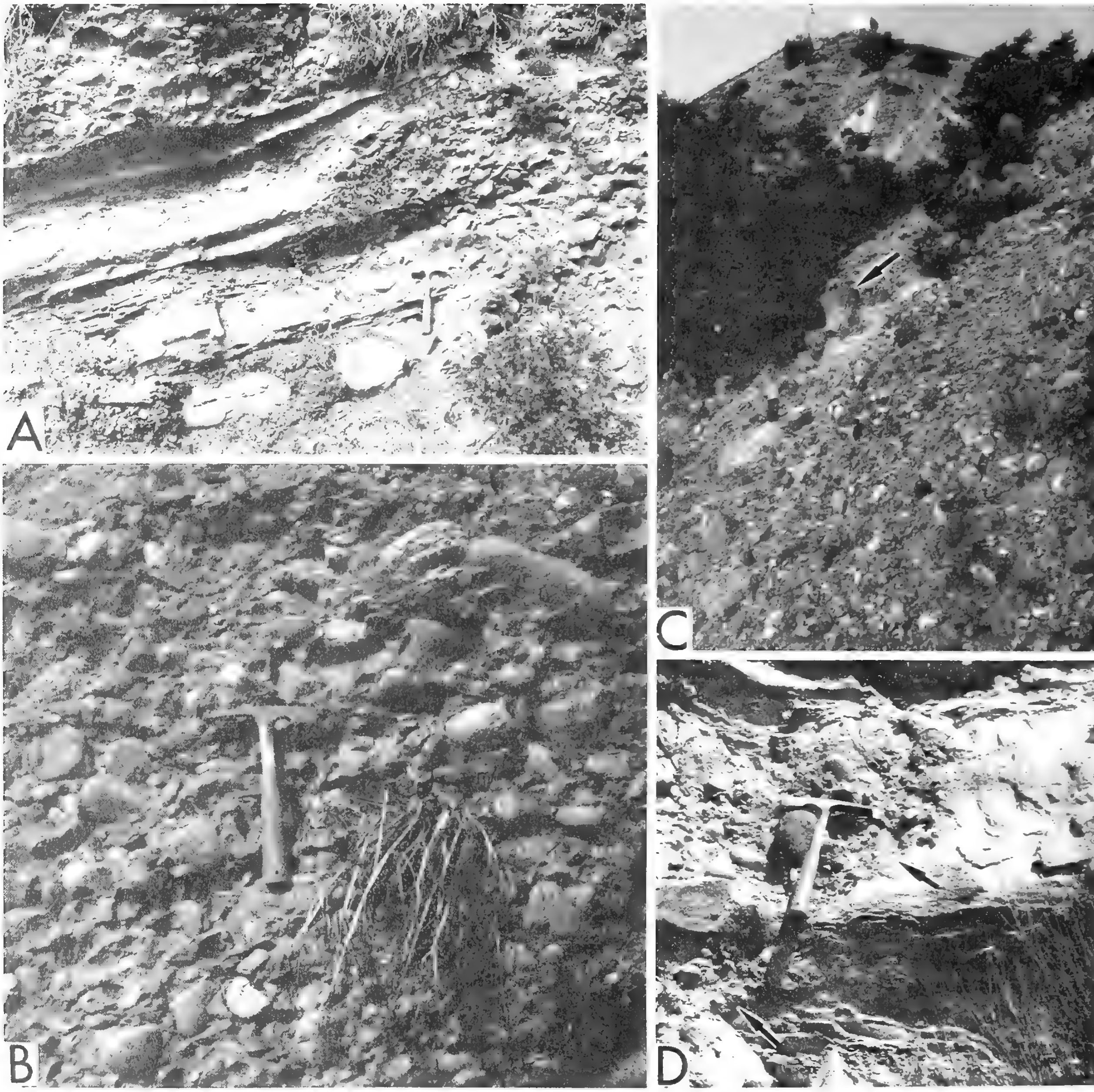

FIGURE 4.—Examples of coarse channelized facies association: *A*, clast supported conglomerate channel fill that truncates thin sandstone and siltstone section (megasequence B, just below village of Saint-Antonin); *B*, more detailed photograph of channel fill shown in *A*; *C*, thick channelized and lenticular sequence of coarse (arrow points toward block > 2 m^3) conglomerate and pebbly sandstone, megasequence B, NE of Saint-Antonin; *D*, small channel (lag filled, clast supported conglomerate) truncating a sandstone layer, same location as *C*. (Hammer = 28 cm.)

FIGURE 5.—Examples of coarse lenticular facies association: *A*, inverse-to-normal graded, matrix supported conglomerate (arrow shows base of unit truncating underlying pebbly sandstone layer); *B*, alternating pebbly sandstone and pod- and irregularly shaped conglomerate strata; *C*, disorganized pebbly sandstone showing cut-and-fill structure (arrow). (All sections SE of St. Pierre, about 4 km W of Saint-Antonin; hammer = 28 cm.)

several varieties: pebbles are distributed as distinct, often thin, layers within coarse sandstone, and (usually) concentrated along horizontal (Figure 8A) or foreset stratification boundaries (clasts are commonly imbricated); or pebbles and cobbles are inversely graded in the lower part of sandstone units and progress upward as normally graded series (Figure 9A) (clasts occasionally are imbricated); or coarse clasts (pebbles usually <5 cm) concentrated as the base of beds are normally graded, and then topped by coarse sandstone or pebbly sandstone layers (Figure 9B).

Sedimentary structures commonly observed in the lenticular association include large variably shaped rip-up clasts of shale and sandstone in both sandstone and conglomerate layers (Figure 10A, B). Also noted are armored mud-balls and rip-up shale clasts enclosing large pebbles (Figure 10C), and large individual pebbles or cobbles isolated in sandstone layers. Plant matter is ubiquitous and locally concentrated as thin lignite lenses or, more commonly, as small flakes, often with mica, along stratification surfaces (Figure 2A, B). A relatively low proportion of sandstone and conglomerate layers are deformed, and these are interpreted as slumps (Figure 10D) and pos-

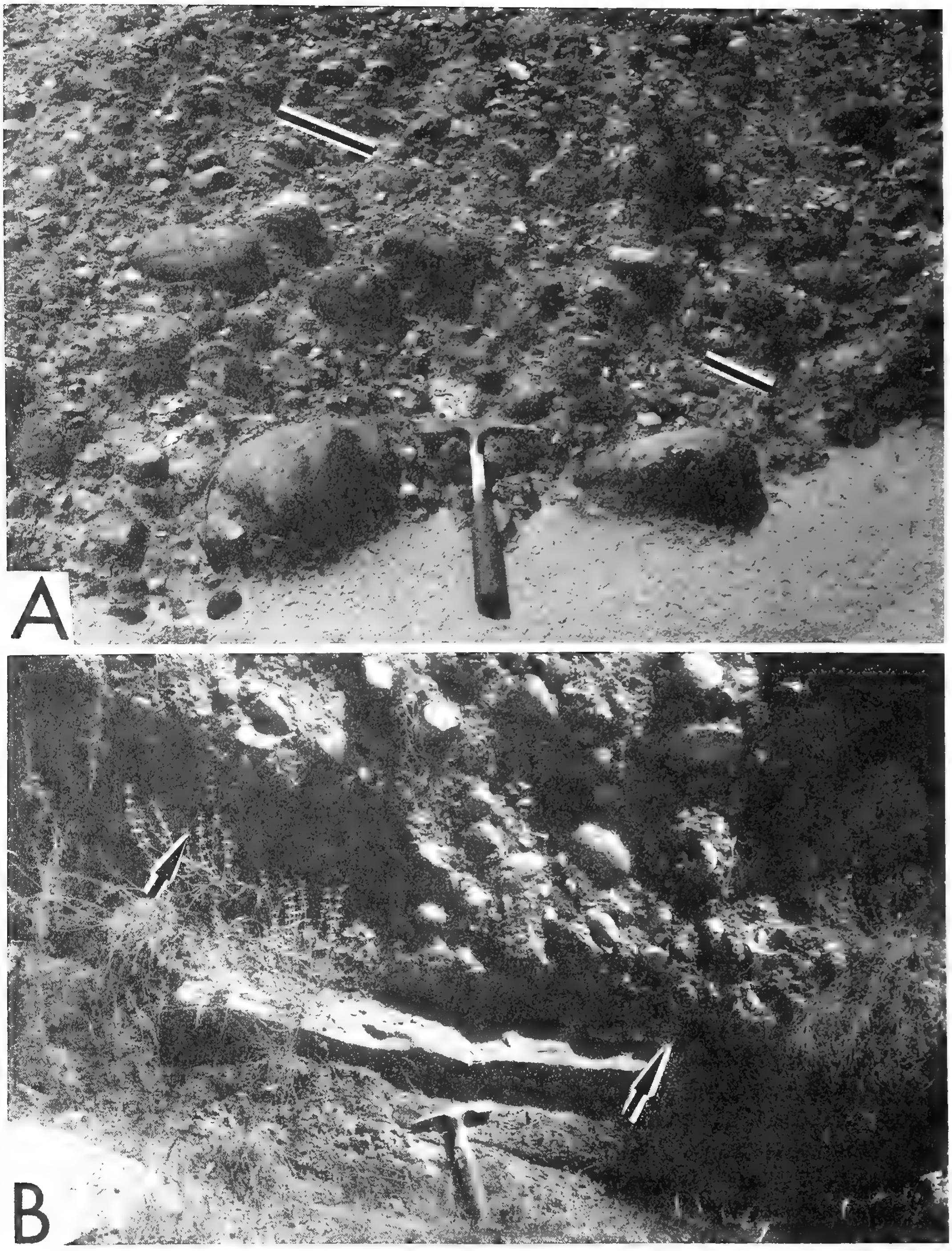

FIGURE 6.—Examples of structures in coarse lenticular facies association: *A*, matrix supported conglomerate with clasts showing some imbrication of elongate pebbles (bars highlight the *a* axis of clasts dipping upslope toward SE), basal cobbles, and boulders resting within top of underlying coarse, poorly sorted sandstone, section SE of St. Pierre; *B*, sharp based (arrows), clast supported conglomerate truncating underlying sandstone layer, megasequence B, NE of Saint-Antonin. (Hammer = 28 cm.)

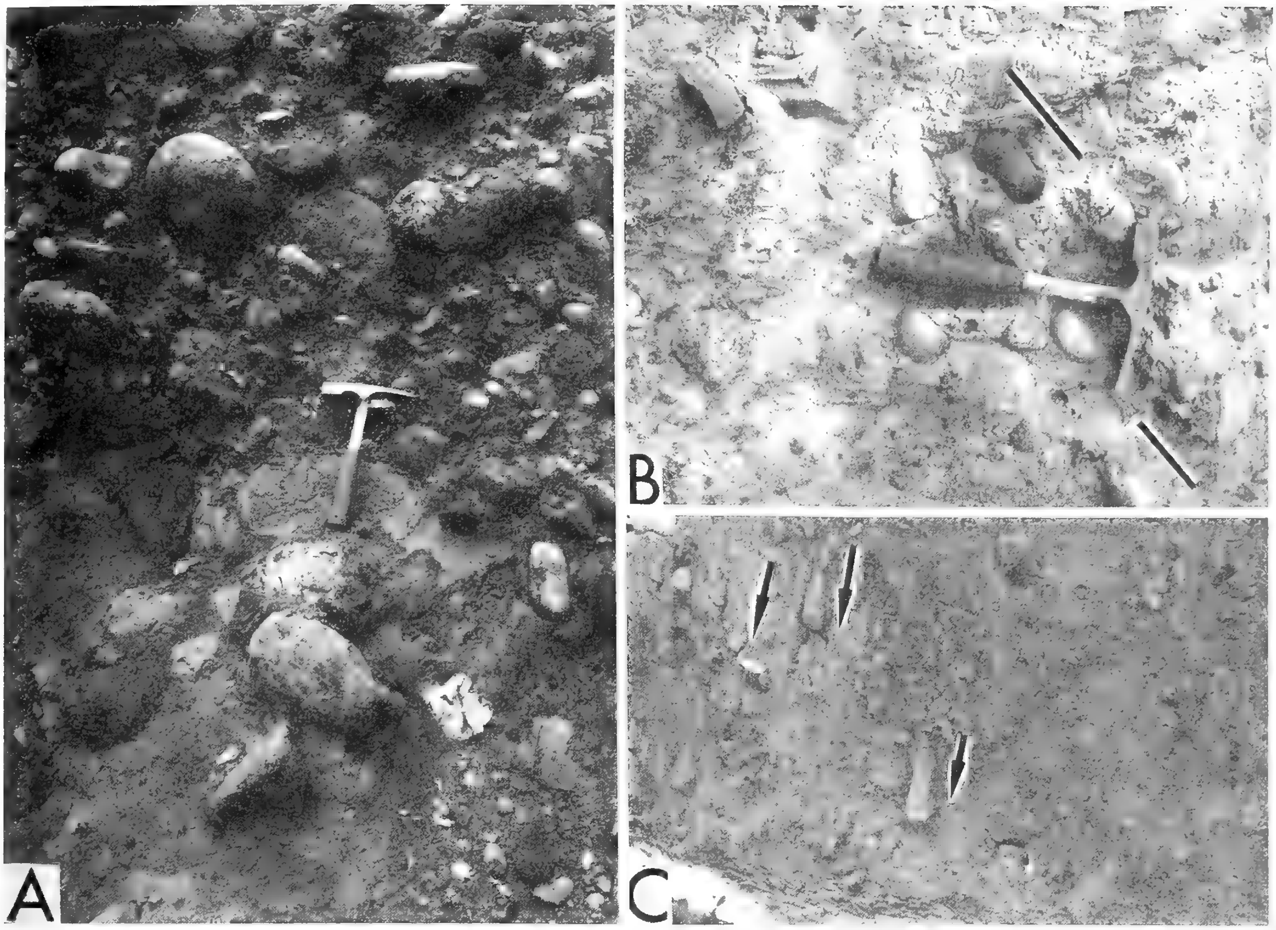

FIGURE 7.—Examples of fabric in coarse lenticular facies association: *A*, disorganized, matrix supported conglomerate in contact with overlying unit showing some imbrication of large, elongate clasts (S of La Penne); *B*, pebble orientation in sandy mud matrix, viewed from above, elongate *a* axis of clasts oriented subparallel to flow (megasequence A, SW of Saint-Antonin); *C*, pebble-produced tool markings (elongate *a* axis of pebbles oriented transverse to flow, arrows) on sole of coarse conglomerate (megasequence B, NE of Saint-Antonin). (Hammer = 28 cm.)

sibly liquefied deposits (Figure 10E).

Both disorganized lenses and some channel units comprise subrounded to rounded subspherical andesitic boulders, particularly the upper conglomeratic series of megasequence A (Figures 1, 3B) and many of the coarse layers of megasequences B and C (Figure 3A). The composition of this extrusive volcanic material and of subaqueous breccia flows between and within coarsening-upward series has been described by Bodelle (1971).

FINE-GRAINED SHEET ASSOCIATION.—This assemblage comprises several types of deposits. The thickest (50 m to 150 m or more) are alternating silty shale and laminated siltstone and sandstone sections that form the base of coarsening-upward megasequences (Figure 11E). Some thin, poorly graded siltstone beds (1 to 5 cm) resemble T_{c-e} turbidites, and display trace fossils and tool markings oriented primarily toward the NW and WNW. Similar but much thinner sequences of fine-grained alternations and moderate to well-stratified sandstone layers are interbedded within coarser strata of the lenticular assemblage. Graded sandstone strata with sole marks and flame structures (Figure 11C) are identified as T_a,

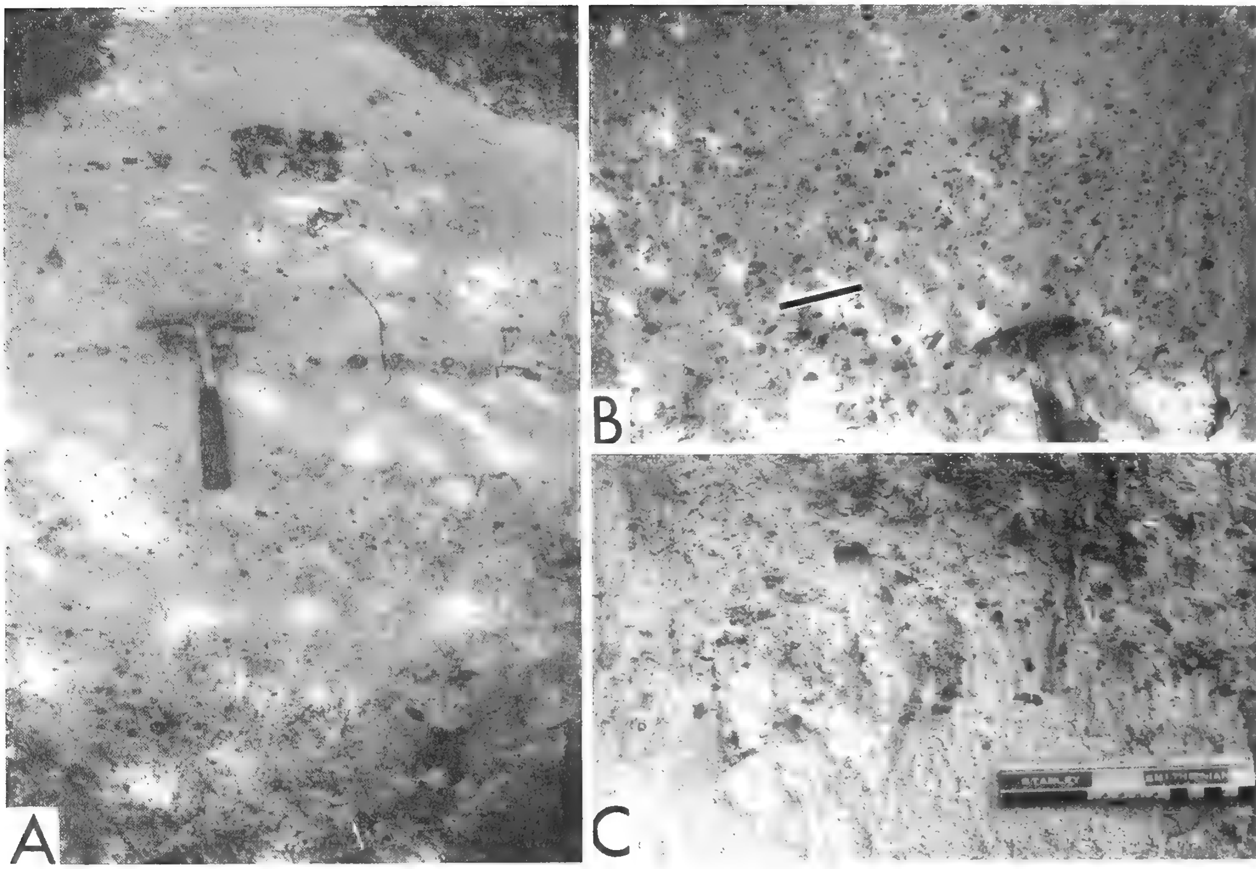

FIGURE 8.—Examples of stratification structures in coarse lenticular facies association: *A*, stratified pebbly sandstone; *B*, *C*, pebbles irregularly dispersed in coarse sandstone, all in megasequence A, SW of Saint-Antonin. (Bar in *B* highlights imbrication pattern of some pebbles; hammer = 28 cm; ruler scale = 15 cm.)

T_{a-b} (Figure 11B) and T_{a-c} (Figure 11A) turbidites. Most well-stratified sandstone and finer-grained layers, truncated by channelized (Figure 11D) and coarser units (Figure 5B), cannot be traced beyond several hundreds of meters within the composite lenticular association.

Proximal Slope–Slope Basin Fan Model

A depositional model for the Saint-Antonin-Conglomerate, including the coarsest series, is formulated on the basis of several lines of evidence summarized below. A very generalized schematic depiction is presented in Figure 12.

The formation is marine, a conclusion reinforced by the faunal content. Foraminiferal assemblages in the upper part of the Marnes bleues shales (listed in Bodelle, 1971), and fauna more recently collected in the silty shales of megasequences B and C (Table 1) include both benthic and planktonic forms. Caution is needed in interpreting these assemblages because both well-preserved autochthonous faunas and those reworked from older sections occur together; the latter, usually abraded, altered, and iron-stained, are more commonly encountered in the coarser layers. The fresh pelagic tests, including *Globigerina* and *Catapsydrax* (Table 1), probably accumulated on a silty mud bottom in a relatively open marine realm, away from the immediate influence of a high-energy coastal or shallow water regime. None of the benthic species are living today, but

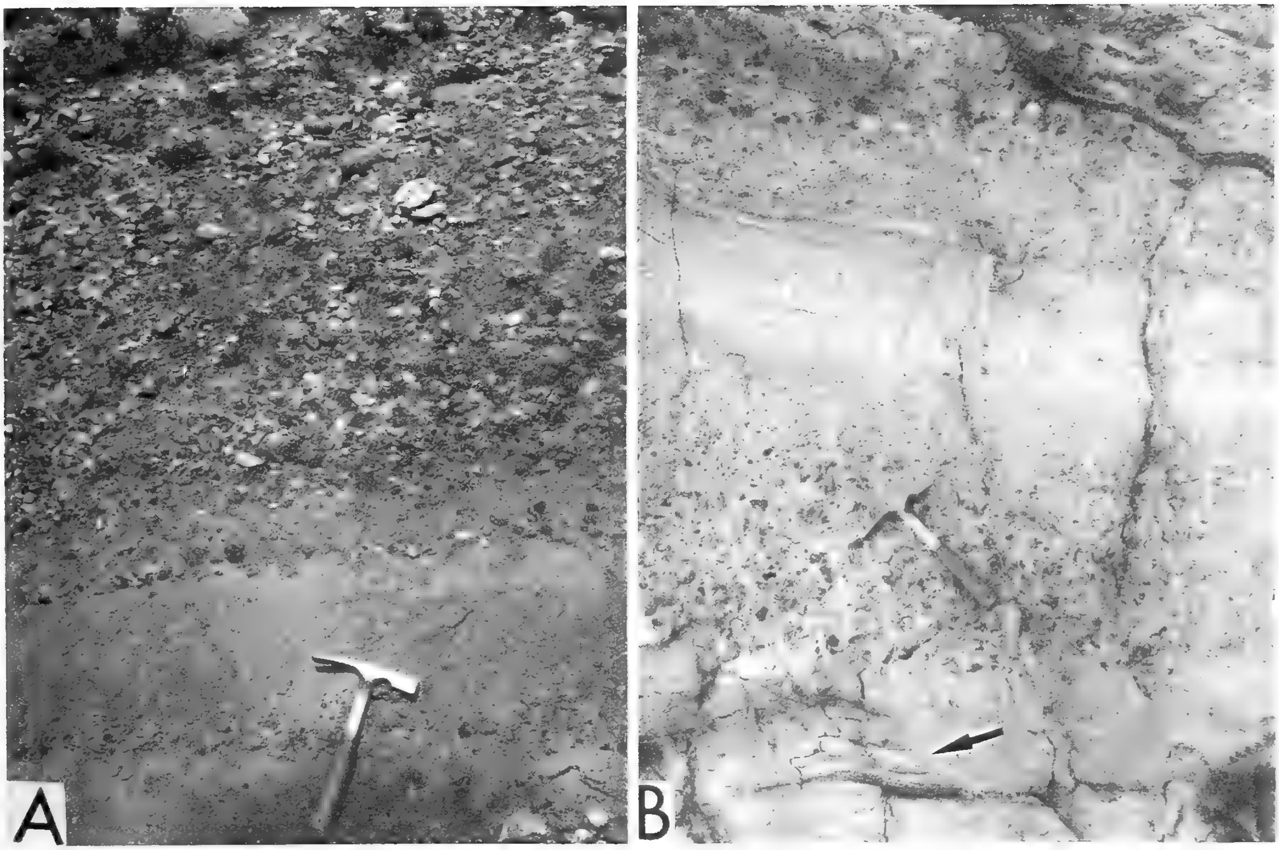

FIGURE 9.—Examples of stratification structures in coarse lenticular facies association, pebbly sandstone units (megasequence A, SW of Saint-Antonin): *A*, reverse graded; *B*, normally graded (note truncation of plant-rich sandstone layers, arrow, by coarse sandstone). (Hammer = 28 cm.)

a comparison at the generic level with modern assemblages suggests that the finer-grained terms of megasequences were deposited in an outer shelf to upper bathyal setting, and minimal depths of 100 to 200 meters are proposed (G. Glaçon, pers. comm. 1978).

The formation appears to record the direct depositional influence of a coarse alluvial system on the adjacent land. It is recalled that laminated siltstones forming the finer-grained sections below the sandstones and conglomerates of megasequences A, B, and C comprise abundant plant material and display structures indicative of both traction and gravity flows, suggesting a pro-deltaic slope environment. The poorly sorted, plant-rich, current-stratified massive sandstone above these are likened to modern delta front lenses and associated distributary channels (Coleman and Wright, 1975), rather than to more texturally mature, shelly nearshore sand bodies (cf. Hechel, 1972). The overlying conglomerate series constitutes a facies not commonly encountered in the typical modern mud-to-sand deltaic constructional model. The initial phase of cobble and boulder transport would almost certainly involve dispersal directly to an offshore margin from mountain torrents and an alluvial fan system positioned between a mountain base and the coast; gradient, proximality to source and vigorous periodic flooding are implied (Figure 12). The large volumes of coarse material spread along broad sectors of the basin margin also would suggest input from a partially submerged fan delta system backed by alluvial fans.

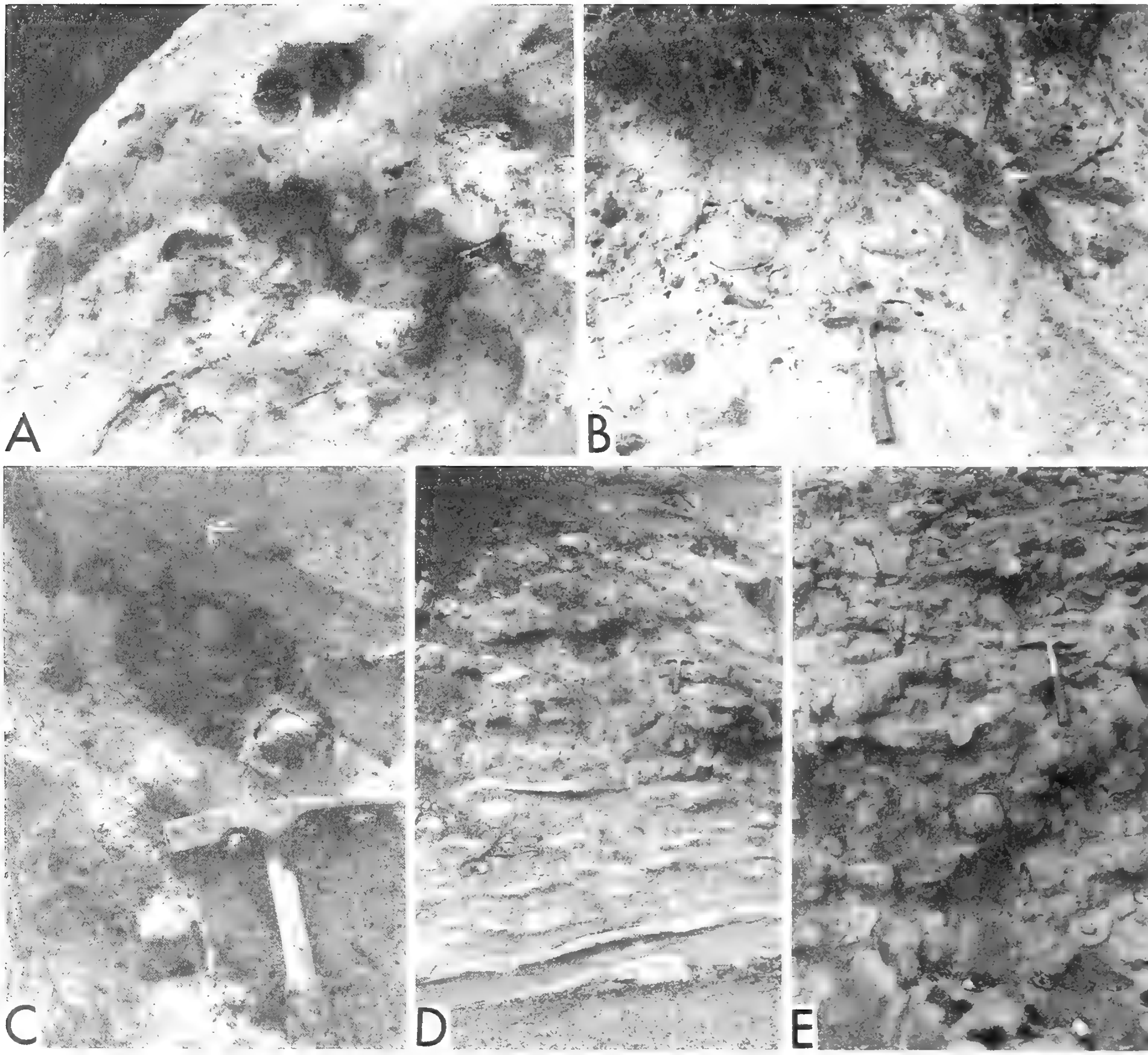

FIGURE 10.—Examples of structures in coarse lenticular facies association: *A*, large shale rip-up clasts in sandstone; *B*, conglomerate; *C*, shale clasts enclosing rounded pebbles in a coarse sandstone layer. (*A*, *B*, *C*, megasequence A, SW of Saint-Antonin); *D*, *E*, deformed pebbly sandstone layers S of La Penne. (Hammer = 28 cm.)

The depositional environment of the Saint Antonin Conglomerate in the study area is a proximal subaqueous slope. (1) Some of the thinner, better stratified sandstone sheets associated with the massive sandstone and conglomerate lenses are graded and display moderately developed T_a, T_{a-b}, and T_{a-c} sequences, flame structures and tool markings that for the most part are consistently oriented toward the NW and WNW. This consistency of sole mark directions at the base of graded beds indicates emplacement by sediment gravity flows, probably turbidity currents, on a subaqueous slope rather than by storm stirring on a marine platform. (2) A slope origin also is favored by the association of slump deposits, very large (>1 m diameter) crystalline boulders, and inverse-to-normal and normal grading displayed by some matrix- and clast-supported conglomer-

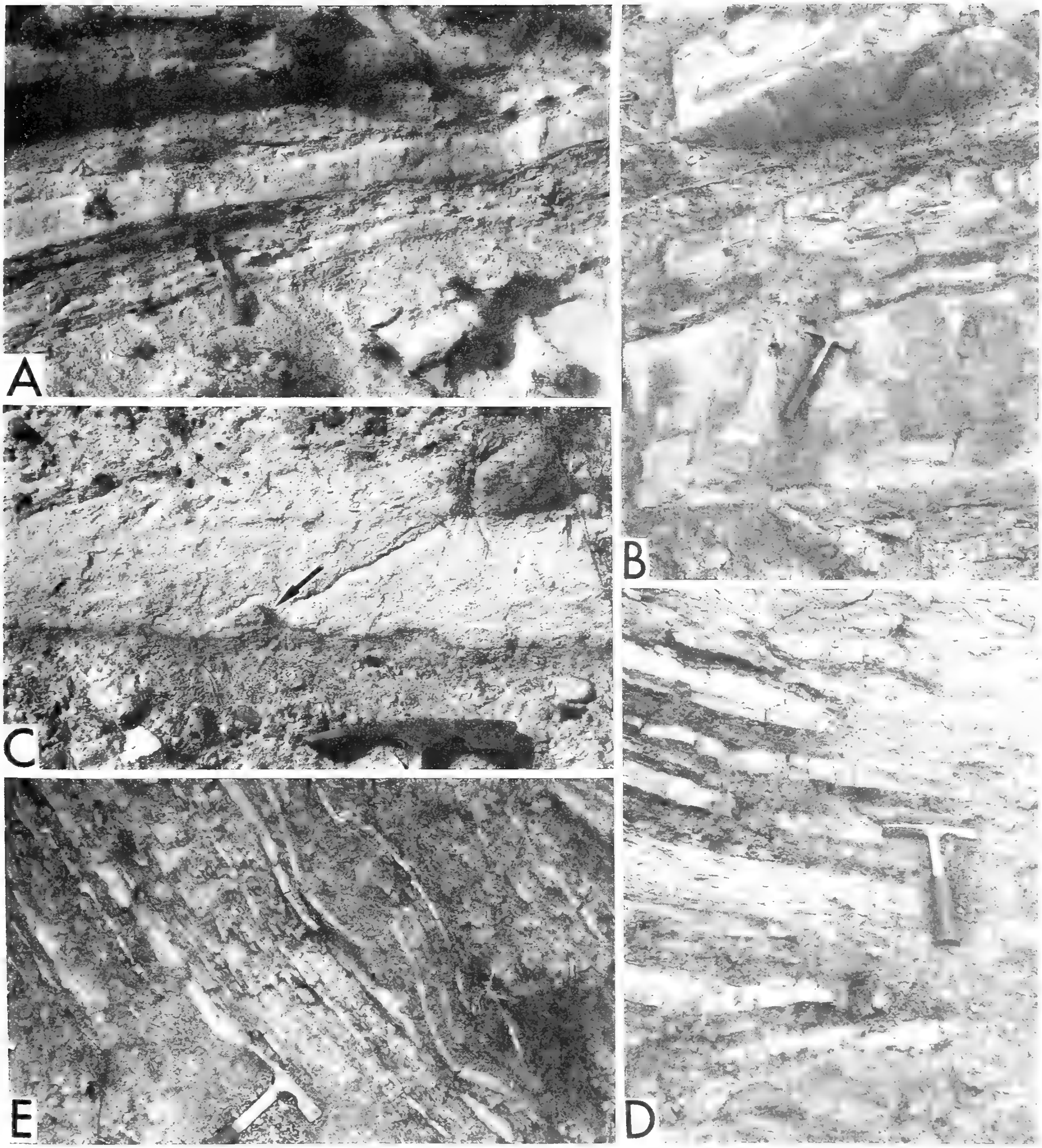

FIGURE 11.—Examples of the fine-grained sheet association: *A*, graded sandstone layers, T_{a-c} sequence; *B*, same, T_{a-b} sequence; *C*, same, sole markings and flame structures (arrow) at base of a graded layer; *D*, sandstone-shale sequence truncated by a pebbly sandstone unit; *E*, laminated siltstone-shale section, lower term of megasequence C, NE of Saint-Antonin. (Hammer = 28 cm.)

ates and pebbly sandstones. (3) The slope was submarine as indicated by Bodelle's (1971) clast shape analysis that showed coarse, fluvially derived debris mixed with pebbles that record abrasion in a coastal setting; these conglomerates are covered directly by finer-grained facies containing marine microfossils. (4) The slope in the eastern and central part of the study area was oriented toward the NW on the basis of sole mark and small channel axis orientation, foreset lamination, and *a* or *b* clast axis imbrication. (5) Interpretation of the interbedded volcanic cobbles, boulders, and andesitic breccia flows as lahars (Bodelle, 1971) would be consistent with a subaqueous slope setting (Figure 12).

Any comprehensive sedimentation model must take into account a potential tectonic component. Regarding the Saint-Antonin Conglomerate, there is indirect evidence for strong structural control: accumulation was concurrent with progressive uplift of terrains south of the basin margin. This is recorded by a marked increase, in the upper megasequences, of coarse sedimentary debris that can be specifically related to adjacent Mesozoic and early Tertiary terrains. Eocene Marnes bleues shales and older Saint-Antonin sandstone debris in megasequence B and C further attest to the rapidly changing configuration and accelerated erosion of exposed Eocene sections immediately south or southeast of the southern limb of the Saint-Antonin syncline. This concurrent deformation maintained the gradient between source terrains and the coast, thus prompting continued northward transport of sand to boulder-size debris directly onto the alluvial fan-delta front and adjacent coastal sector. Syndepositional faults are not mapped, but unconformities within the formation record uplift of adjacent land and the progressive shift of the coastline and basin margin toward the north and northwest; some depression of the slope in the form of a perched basin also may have occurred during deposition. The gypsum in the uppermost shales above megasequence C is probably associated with a progressive shallowing of the slope and basin and their eventual emergence in the early to mid Oligocene.

The tectonic-sedimentation interplay would account for the appearance of conglomeratic series that forms an integral part of the proximal submarine slope sequence. The depositional model envisioned here depicts fan delta growth directly on a mobile tectonically-formed slope rather than on a low-gradient shelf platform. Such conditions would provide a substantial delta front slope that facilitated failure of rapidly deposited metastable sequences by overloading during flood and volcanic events, and by earthquake vibration. The combination of periodic failure and structurally-induced diversion of fluvial systems and delta switching produced a back-and-forth migration of coarsening-upward tongues downslope from the delta proper. This process resulted in the lateral spread of a series of coalescing terrigenous cones across a broad sector (<10 km) of the upper margin; the major sediment build-up (>1000 m) appears to have occurred in the southeastern part of the syncline, possibly in a slope basin.

The model for the Saint-Antonin Conglomerate also should incorporate the observed spatial-temporal organization of major facies components, i.e., channelized, lenticular, and sheet. Each progradational coarsening-upward megasequence is dominated by a network of migrating channels (the fills exposed in the study area are too small and shallow to be submarine canyon deposits) that intertongue with lenses consisting of diverse fine-to-coarse-grained stratification types. This arrangement broadly defines a channel and lobe arrangement that calls to mind a moderately well-organized fan system. If such a system is applicable, then the finer-grained sandstone sheets and siltstone-shale sequences interbedded or interfingering with the coarser lenses are identified as channel overflow, interlobe, and more distal fan deposits. The thicker and regionally more extensive silty shale sequences accumulated in sectors where active progradation was reduced and lobes temporarily abandoned. Large fan-head channel fills are not recognized. It is presumed that these and associated nearshore delta-front series deposited on the uppermost slope in the sector immediately south of the southern limb of the syncline have been removed by

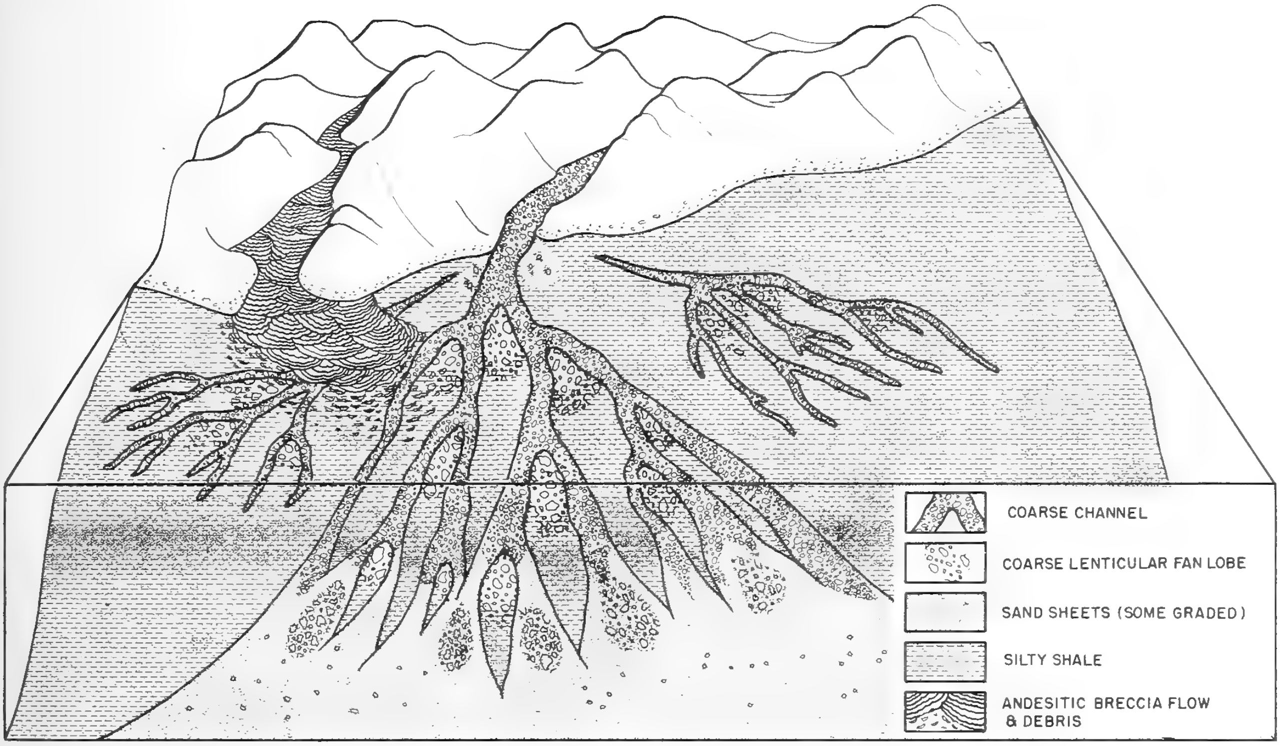

FIGURE 12.—Scheme of coarse sedimentation, slope model based on study of Saint-Antonin facies associations; diagram depicts active fan-like, prograding channel-lobe and abandoned systems, below a fan delta, on a tectonically active submarine margin bounded by a coastal range.

erosion.

The exposures in the Saint-Antonin syncline record primarily the submerged portion of the coalescing fan-progradational cone below the fan delta front complex. On the basis of good to excellent quality outcrops, it is possible to ascertain that the facies organization pattern, dominant stratification types, and the dimensions of individual pebble- to boulder-rich layers, in some respects, are different from previously described ancient conglomerate-bearing base-of-slope (Ricci Lucchi, 1969; Shideler, 1970; Lowe, 1972, Stanley and Hall, 1978) and coarse deep-sea fan deposits (Davies and Walker, 1974; Carter and Lindqvist, 1975; Piper, et al., 1978). The latter generally comprise series of channel conglomerate deposits, associated with well-defined fining- or coarsening-up sandstone turbidite and mudstone lobe sequences (cf. Mutti and Ricci Lucchi, 1972). The Saint-Antonin facies distribution patterns are considerably less well organized and appear more similar to some modern alluvial fans (Blissenback, 1954; Bluck, 1964; Bull, 1964; 1972; Hooke, 1967) and ancient coarsening-up alluvial cycles (Steele, et al., 1977; Heward, 1978) than to classic submarine fans. In the vicinity of the village of Saint-Antonin, for instance, the pebble and cobble channel-interchannel distribution pattern of megasequences A and B is comparable to the Trollheim Fan of California described by Hooke (1967, fig. 4).

Subaqueous displacement of pebble- to boulder-size material involved high-concentration dispersion, probably with some bed-load traction. As in the case of alluvial fans, it would appear that the prevailing emplacement mechanism for many conglomerates and pebbly sandstones, particularly the poorly sorted and irregularly stratified units and lobes, is debris flow. This transport process, which has received much attention in recent years (Johnson, 1970; Hampton, 1972; Beaty, 1974; Enos, 1977) implicates (1) large clast

support by a mixture of interstitial fluid and fine sediment ("matrix"), (2) finite yield strength (cohesion), and (3) flow motion as a series of waves and surges. As generally conceived, debris flows would best account for the disorganized conglomerates in some channels and in many coarse fan lobes. However, the diversity of stratification and fabric displayed by clast- and matrix-supported conglomerates and pebbly sandstones strongly suggest that debris flow as used here likely encompasses, and is associated with, a spectrum of high-density subaqueous gravity flow mechanisms (Fisher, 1971; Middleton and Hampton, 1973). Structures such as inverse grading, or inverse-to-normal grading, normal grading, and preferred fabric (orientation and imbrication of clasts) indicate that at some point during flow, clasts were able to move freely relative to each other. Dispersive pressure (Hampton, 1972), release from suspension (Davies and Walker, 1974) and a bed-load traction component related to turbulence (Winn and Dott, 1977) may be invoked, respectively, for inverse grading, grading and imbrication, and the traction structures observed.

As in many natural physical systems, a gradational sequence probably develops during a single high-concentration dispersion event: changes occur with time and from one point to another within the flow. Some examples of sequential gravel facies evolution have been illustrated by Walker (1975) and Carter and Norris (1977), but these do not appear directly comparable with the time-space organization patterns of Saint-Antonin pebble to boulder series observed in this study. The prevailing association of disorganized and inverse graded-to-graded conglomerate types, and the low proportion of graded-to-stratified conglomerate types (terminology of Walker, 1975) are largely a function of deposition on a steep slope in a very proximal setting unlike the more distal, gentle gradient, base-of-slope or submarine fan environments modeled by Walker and other authors.

The presence of deformed conglomeratic strata allows for, but in no way proves, the transformation of slumps to debris flows and associated highly charged dispersion flows following failure at the fan delta front. Some evidence of progressive distal facies changes is recorded by the somewhat higher proportion of finer conglomerate in sections of the northern syncline limb. The short transport distance between failure point and depositional site probably accounts for the low percentages of graded pebbly sandstones and well-developed sandstone turbidites.

Although one tends to be most impressed by the coarser conglomerate units, it should be noted that failure of the fan delta front did not, in every case, initiate highly charged en masse and debris flow transport in channels or result in debris flow emplacement in lobe or interlobe settings. The graded sandstone and better stratified siltstone-shale sections indicate that floods triggered less-dense flows, including turbidity currents. Some further insight on this phenomenon is provided by the Annot Sandstone "grès d'Annot" sections at Puget-Théniers, about 6 km to the north of La Rochette, and at adjacent localities (Rouaine, Scaffarels, etc.). These sections north of the Saint-Antonin syncline are approximately time-equivalent to megasequence A and are formed largely of coarse sandflow and turbidite units that comprise significantly lower amounts of pebbles and virtually no cobble-size debris; they are identified as base-of-slope deposits that accumulated seaward in deeper, more distal sectors of a relatively large basin (Stanley, 1975). If, as earlier suggested in the present study, minimal slope depth at La Rochette was 100 m, a rough estimate of the depth of the slope-basin interface at Puget-Théniers can be made: depths of about 400 m, 600m, and 1200 m, respectively, are calculated if slopes of 3°, 5°, and 10° are assumed between La Rochette and Puget-Théniers. Steep slopes (probably at least 5° to 10°) are favored on the basis of the assemblage of stratal types forming the Saint-Antonin Conglomerate, and postulated basin depths of at least 1000 m at Puget-Théniers conform with other paleogeographic analyses (Stanley, et al., 1978; Stanley, 1980). The lack of conglomerates in the deeper water-time equiva-

lent sandstones at Puget-Théniers suggests that some coarse debris may have been trapped in depressions, perhaps perched basins, on the slope.

The coarse facies described in this study represent an important, but often poorly exposed, component of ancient mobile belt margins, and as such the Saint-Antonin Conglomerate proximal submarine slope model as depicted on Figure 12 may be applicable to some similar sequences in the rock record. Substantial refinement of this depositional model is required, however, and some insight is provided by evaluating potential analogs. The Quaternary Var River–Var Delta steep slope gravel complex west of Nice on the Mediterranean coast southeast of the study area (Figure 1), for example, presents some attributes comparable to the Saint-Antonin Conglomerate. At this locality, coarse debris from the adjacent Maritime Alps and some reworked from adjacent beaches are mixed with silty mud and accumulate on a steep margin slope within a short distance from the beach (Stanley and Unrug, 1972). Periodic displacement of coarse debris at the delta front and upper slope is recorded, particularly at times of flood, and Bourcart (1964) and Gennesseaux (1966) have shown that this material is transported downslope by gravity-induced mechanisms all the way to the Ligurian Basin plain.

The fan-like submarine slope progradation of the Saint-Antonin Conglomerate, unlike that of the modern Var gravel delta, minimizes the role of submarine canyon channelization. The model depicted in Figure 12 emphasizes the back-and-forth lateral migration and build-up of coarse tongues as well as the interplay of structural mobility, associated volcanic activity and floods as basin margin triggering mechanisms. More comparable depositional analogs are the Pliocene Ridge Basin series of California where coarse debris was shed directly into a deep lacustrine setting (Link and Osborne, in press) and the marine Eocene-Oligocene conglomerates of the Santa Ynez Mountains, California, deposited on structurally mobile slopes (Van de Kamp, et al., 1974). Modern marine counterparts would likely be encountered on the leading edge of plates and orogenic settings such as rift margins where coastal ranges provide large volumes of sand- to boulder-size material directly onto margins where shelves are narrow or absent (Crowell, 1974; Dickinson, 1974; Okada, 1974; Friedman and Sanders, 1978: 302–306). Particularly favorable conditions in such regions as the Red Sea or Gulf of California probably occurred in the late Pleistocene when, as a result of substantial lowering of sea level, sediments were emplaced directly at the shelf edge and uppermost slope. There is a need to document both the deposits and processes on modern narrow, steep submarine margins bordered by coastal regions where coarse terrigenous debris is being transported to deep settings.

Summary

The depositional history of the latest Eocene to early Oligocene Saint-Antonin Conglomerate series in the French Maritime Alps is reviewed:

1. The three stratigraphic members that form the Saint-Antonin Conglomerate (defined by Bodelle, 1971) serve as datum references to identify the spatial and temporal distribution patterns of silty shale-siltstone, sandstone, and conglomerate sections in the Saint-Antonin syncline.

2. These marine facies form coarsening-upward successions, or megasequences (termed A, B, and C in the eastern part of the syncline), that are discontinuous along the E-W depositional strike.

3. The basal term of each megasequence consists of silty shale-siltstone alternations that contain microfossil assemblages indicative of open marine, outer shelf to upper bathyal conditions, and minimal depths of 100 to 200 meters; the petrology and abundance of plant matter in siltstone layers suggest proximity to a fan delta system.

4. The megasequences comprise coarse channelized, coarse lenticular, and fine-grained sheet facies associations probably organized as a network of migrating channels and sequences of strata that resemble fan lobes and channel overflow deposits.

5. Debris flow and associated high-concentration dispersions are responsible for the emplacement of poorly sorted, disorganized conglomerates and some partially organized (crudely stratified, inverse graded, prefered clast fabric) conglomerates and pebbly sandstones; failure at the submerged delta front induced slumping and turbulent flows with some bed-load traction, and also turbidity currents that released graded siltstone, sandstone, and pebbly sandstone layers.

6. There are insufficient data to demonstrate transformation of slumping to debris and turbidity current flow within the study area, and the lack of an obvious sequential transport-depositional pattern is largely a function of sedimentation in a proximal setting; it is possible, however, that high-concentration dispersions evolved to turbidity currents further downslope, based on study of time-equivalent deposits in more distal, deeper-water Annot Basin settings.

7. The facies successions, assemblage of stratification types and sedimentary structures, and size of individual strata recall alluvial fans rather than the more commonly described and better organized gravel-rich base-of-slope and submarine fan deposits.

8. Coarsening-upward megasequences are interpreted as a progradational system of coalescing fans deposited below an alluvial fan-backed submerged fan delta complex; deposition occurred directly on a slope, or in a proximal slope basin rather than on a gentle base-of-slope to basin gradient.

9. The proposed depositional model invokes a strong tectonic overprint as recorded by progressive uplift of terrains south of the basin margin, northward shift of the coastline and basin margin, andesitic flows, and the structurally induced diversion of fluvial systems and delta-switching; the interplay of these phenomena produced an irregular back-and-forth migration of the coarsening-upward tongues on the structurally mobile slope.

10. Modern counterparts of the Saint-Antonin Conglomerate fan-like progradational patterns, involving tectonics and vigorous sedimentation on a slope, probably occur on the leading edge of plates and on other structurally-active, coastal chain-bounded margins where coarse terrigenous sediment is transported directly onto mobile slopes. Definition of coarse deposits and processes responsible for their emplacement in modern tectonically mobile settings is needed.

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